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Gamma Ray Bursts: basic facts and ideas

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Abstract. The recent years witnessed a dramatic improvement in our knowledge of the phenomenology and physics of Gamma Ray Bursts (GRBs). However, our "pillars of knowledge" remain a few, while many aspects remain obscure and not understood. There is no general agreement on the radiation mechanism of the prompt emission, nor on the process able to convert the bulk motion of the fireball into random energy of the emitting leptons. The afterglow phase can now be studied at very early phases, showing an unforeseen phenomenology, still to be understood. In this context, the detection of $\sim$GeV emission from $\sim$10% of GRBs, made possible by the *Fermi* satellite, can hopefully shed light on some controversial issues.

Keywords. gamma rays: bursts, radiation mechanisms: nonthermal, supernovae: general

1. Pillars of knowledge

What are the fundamental and not controversial facts characterizing Gamma Ray Bursts? I propose a list of seven "pillars" of knowledge, selected in an admittedly completely subjective way, following this criterion: If we did not know this particular fact, would we lose a basic piece of knowledge?

1.1. *GRBs are cosmological*

One of the major achievements of the *Beppo*SAX satellite was to localize a GRB with enough accuracy to make the pointing of an optical telescope possible, allowing to find the redshift. At the same time, the afterglow was discovered (Costa et al. 1997, for GRB 970228). As we know, the first measured redshift was $z = 0.835$ for GRB 970508 (Metzeger et al. 1997; the redshift for GRB 970228 was measured later, due to the faintness of its host galaxy).

This ended a long and animated discussion about the origin of GRBs (i.e. "local" , i.e. associated to neutron stars in the Galactic halo, or cosmological, as predicted by Paczynski 1986), and finally set the power of these objects: they are indeed the most explosive events of the Universe after the Big Bang. Soft γ–ray repeaters, instead, were found to be "nearby" magnetars undergoing flares, and associated to supernova remnants.

One of the early successes of the *Swift* satellite was to localize short GRBs, and therefore allow the optical follow up leading to establish that they, also, are cosmological events (Gehrels et al. 2005).

The top panel of Fig. 1 reports the energetics of the GRBs with measured redshifts, and the bottom panel shows the redshift distribution for long and short GRBs. Most of them have been detected by *Swift*. With the caveat that the shown isotropic energetics $E_{\rm iso}$ are not bolometric ones, nor have been K–corrected, we can see that the largest $E_{\rm iso}$ correspond to more than a solar mass entirely converted into energy. Short GRBs with measured z are still very few, but they seem to lie closer and to be less energetic than long ones.

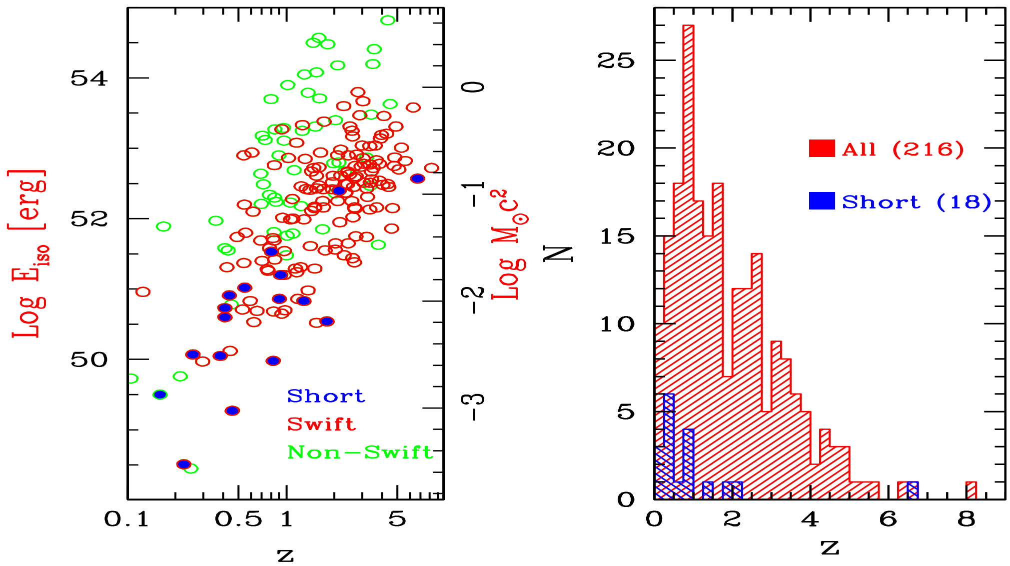

Figure 1. Left: Energetics of the prompt emission of GRBs with measured redshift. Be aware that the plotted energetics are simply the observed fluences multiplied by $4\pi d_{\rm L}^2/(1+z)$, so they are only lower limits to the bolometric $E_{\rm iso}$. Right: Redshift distribution.

1.2. *GRBs have large bulk Lorentz factors*

GRBs are the fastest extended objects of Nature, with bulk Lorentz factors Γ that can exceed 1000. The first evidence came from theory: injecting a colossal amount of energy in a small volume (of the order of a few Schwarzschild radii of size) leads inevitably to the formation of electron–positron pairs that makes the so–called "fireball" opaque to the huge internal pressure. The fireball is then obliged to expand, becoming relativistic with $\Gamma \propto R$ until the internal energy is converted into bulk motion (if the fireball remains opaque).

A nice observational evidence of relativistic speeds came, in the late '90s, from the behavior of the radio afterglow of a few GRBs, whose light curve varied wildly for $\sim$3 weeks, "calming down" after this time. This behavior was immediately interpreted as due to radio scintillation quenched by the increasing size of the radio source. Therefore it was possible to establish the expansion velocity, that turned out to be superluminal, requiring $\Gamma > 4$ after 3 weeks from the trigger (Frail et al. 1997).

A very recent evidence came instead from the detection of GRBs in the GeV energy range by the LAT instrument onboard the *Fermi* satellite. The GeV flux partly overlaps with the emission at lower energies detected by the other *Fermi* instrument (the GBM, sensitive in the 8 keV–30 MeV range). If the two emissions are cospatial, then the variability shown in the GBM dictates that the source must have a minimum Γ–factor, to avoid γ–$\gamma \to e^\pm$ suppression of high energy photons. For these LAT–detected GRBs (10% of the total), the minimum Γ–values are around 1000. (Abdo et al. 2009; Ackermann et al. 2010).

If, instead, the GeV emission is not cospatial with the GBM one, then it is very likely that it belongs to the afterglow phase. The short delay between the GBM and LAT emission can be due to the required time for the onset of the afterglow (i.e. the deceleration time of the fireball moving in the circumburst medium). The shorter this

time, the higher the Γ–factor. Again, for all the LAT detected bursts, values around 1000 are derived (Ghirlanda, Ghisellini & Nava 2010; Ghisellini et al. 2010).

1.3. *Prompt plus afterglow emission phases*

The GRB emission has two phases, the erratic, γ–ray (or hard X–ray) *prompt phase*, and a smoother *afterglow* phase. This means that not all the energy of the fireball is radiated away during the prompt, but some remains. This was predicted before the first observations of the afterglow, but probably at the same time of the detection of long duration GeV emission by the EGRET instrument onboard the *Compton Gamma Ray Observatory* satellite (Meszaros, Rees & Papathanassiuou 1994) and then elaborated by Meszaros & Rees (1997); Vietri (1997); Sari & Piran (1997).

The fact that there are two emission phases suggests that there must be two mechanisms at work, one for the prompt and one for the afterglow.

1.4. *Long and short*

The duration of the prompt emission of GRBs is bimodal, with a minimum around 2 seconds. In astrophysics bimodal distributions are always looked at with suspicion, since malicious selection effects can be at work. The convincing arguments of a real bimodality comes from the spectrum since short GRBs are harder than long ones. This was first evident from the hardness ratio (i.e. the ratio of the flux in two energy bands; Kouveliotu et al. 1993) and then substantiated by direct spectral analysis (Ghirlanda, Ghisellini & Celotti 2004). The bimodality suggests that GRBs come in two flavors, in turn suggesting two different operating mechanisms, and possibly two kinds of progenitors. The prevalent idea is that long GRBs originate immediately after the collapse of a massive, Wolf–Rayet star, while short GRBs originate from the merging of two compact objects.

1.5. *Spikes have same durations*

This "pillar" is not very popular, but it was nevertheless crucial for the development of the current leading scenario of "internal shocks" (see below) explaining the prompt emission. The evidence is that the light curves of GRBs (both long and short) often shows spikes of emission, whose duration $\Delta t_{\rm spike}$ is on average the same (Ramirez–Ruiz & Fenimore 2000). In other words, there is no lengthening of $\Delta t_{\rm spike}$ with t, the time since the trigger. Emission episodes, on average, should then involve regions of similar sizes, and then probably at the same distance from the central engine.

1.6. *Supernova connection*

We believed that long GRBs are associated to Supernovae Ib,c, but not all SN Ib,c are associated to GRBs (Soderberg et al. 2006 estimated a fraction less than 1%). The evidence comes from spectroscopy (for nearby events) and re–brightening of the optical light curve (up to $z \sim 1$). The association strongly indicates that the progenitor of long GRBs is a massive stars, that has lost its hydrogen and helium envelopes. But there are at least two nearby bursts (GRB 060614, Gal–Yam et al. 2006, and GRB 060505, Ofek et al. 2007) where the SN was not found. If present, it would be at least two orders of magnitude less luminous than SN1998bw (associated to GRB 980425).

1.7. *Common behaviors and trends*

"When you see a GRB, you see just one GRB" was a popular motto in the past, meaning that all GRBs were different, with no common behaviors. Now this is not true any longer, and there are indeed common trends and similarities. Just two examples: the spectral energy relation, linking $E_{\rm peak}$ to the prompt energetics or peak luminosity, and the typical

behavior of the early (i.e. less than a day or so) X–ray afterglow, with its characteristic "steep–flat–steep" light curve (Tagliaferri et al. 2005), and superimposed on that, $\sim$1/3 of GRBs show X–ray flares (Burrows et al. 2007). These similarities are the starting point for any serious and general modelling: ideas are in fact abundant, but with no clear prevalence of one over the others.

2. Ideas and enigmas

2.1. *Central engine*

The prevalent idea is that long GRBs are caused by the collapse of a Wolf–Rayet star leading to the formation of a black hole of a few solar masses rapidly spinning. This black hole accretes 0.1–1 $M_\odot$ from a dense surrounding torus for a time more or less equal to the duration of the prompt emission. There are several energy reservoirs: neutrinos, the gravitational energy of the infalling matter, and the rotational energy of the newly formed black hole. The latter is the greatest, since it amounts to $\sim 0.29 M_{\rm BH}c^2 \sim 5.3 \times 10^{53}(M_{\rm BH}/M_\odot)$. The problem is how to extract it efficiently. The leading idea it to use the Blandford & Znajek (1977) process, for which a super–critical magnetic field of $B \sim 10^{15}$ G is required. For short GRBs, the merging scenario assumes two compact objects (e.g. two neutron stars) forming a $\sim 2M_\odot$ black hole surrounded again by a dense accreting torus. The central engine can then be the same for long and short bursts.

Although prevalent, this is not the only idea. Instead of a black hole, one could have, at least initially, a neutron star, (that collapses into a black hole only later, as a re–edition of the Vietri & Stella (1998) Supranova model). This has been proposed both to explain precursors (Wang & Meszaros 2007, see Burlon et al. 2008 for the characterization of precursors). A magnetar has been proposed to explain the flat (plateaux) phase of the early X–ray afterglow (e.g. Lyons et al. 2010). An even more radical idea was put forward by Paczynski & Haensel (2005), who suggested a quark star as the central engine. These authors pointed out that the surface of such a star acts as a one–way membrane, since baryons can only enter, but not escape. Leptons and magnetic fields, instead, can escape. This would help to explain the paucity of baryons in the fireball (i.e. the baryon "loading" problem).

2.2. *Magnetic or matter dominated?*

In the most popular scenario a huge amount of energy is injected into a small volume. Due to the colossal internal energy (and the inevitable creation of $e^\pm$ pairs, making the fireball opaque to radiation) the fireball is bound to accelerate with $\Gamma \propto R$. At the same time the comoving temperature ($T' \propto 1/R$) decreases, and when it goes below $\sim$20 keV almost all the pairs annihilate without being re–created. Still, a small amount of protons and their accompanying electrons ensures that the fireball continues to be opaque until the internal energy is entirely converted into bulk motion. Thus we need another mechanism to re–convert the bulk energy into radiation. This is provided by collisions of different parts of the outflowing relativistic wind moving with different Γ–factors. This are the so–called "internal shocks", occurring at $R \sim 10^{12}$–10^{14} cm, where the fireball has turned transparent (for Thomson scatterings). Then we have a disorder $\to$ order $\to$ disorder process. Lyutikov & Blandford (2003; see the review by Lyutikov 2006 and references therein) advocated instead a simpler order $\to$ disorder process: the acceleration is due to a dominating magnetic field, allowing for almost matter free fireballs. One clear test to distinguish is the so–called "optical flash", occurring when the fireball starts to be decelerated by the interstellar medium: if it is matter dominated, then a reverse shock develops, that originates an important, and fastly decreasing, emission

component (predicted in the optical or in the IR), that would be absent in magnetically dominated fireballs. Indeed optical flashes have been seen, but in a very small fraction of bursts, so the issue is unsettled. Another diagnostic would be polarization of the prompt emission (see the review by Lazzati 2006), that awaits for hard X–rays polarimeters and observations.

2.3. *Internal shocks?*

Collisions between different parts of the relativistic wind (Rees & Meszaros 1994) leading to "internal" dissipation is the leading idea for the dissipation mechanism for the prompt emission. What can be dissipated is only the *relative kinetic energy* of the two colliding parts or shells. The process has then a "built in" low efficiency (e.g. Lazzati et al. 1999). Consider also that, as a result of the dissipation, we distribute the available energy to protons, magnetic fields and leptons. Only the energy given to the latter can be efficiently transformed into radiation. After the different parts of the fireball have collided and "merged", the fireball runs into the circumburst medium, originating a forward "external" shock. This collision is with not–moving material, and should be much more efficient, since the entire kinetic energy of the fireball can be used. The foreseen densities and energies ensure that leptons initially radiatively cool rapidly (fast cooling regime). Thus, at least initially, the resulting afterglow is an efficient radiator. The energy radiated by the afterglow should then be greater than the energy radiated during the prompt phase. We observe just the opposite (e.g. Willingale et al. 2007): $E_{\rm prompt}/E_{\rm afterglow} \sim 10$.

2.4. *Radiation process of the prompt*

The popular choice is that it is synchrotron emission. Shocks should indeed accelerate electrons to relativistic energies, and amplify magnetic fields, making the synchrotron option a natural one. On the other hand, we also require any emission process to be efficient, making the electron to cool completely in a timescale much shorter than any conceivable dynamical or integration time. The spectrum produced by a cooling electron population cannot be harder than $F(\nu) \propto \nu^{-1/2}$. The spectra of practically all bursts are harder than that, and a minority are even flatter than $\nu^{1/3}$, the low frequency tail of the spectrum produced by a non cooling electron population (Preece et al. 1998; Ghisellini et al. 2000). Continuous re–acceleration or heating of the electrons is not compatible with the idea of internal shocks (in which each electron is energized only once), and other possible "way–outs" (adiabatic expansion, steep gradients of the magnetic field, contribution from synchrotron self–Compton) face severe problems as well. Alternatives have been proposed [such as jitter radiation (Medvedev 2000); quasi thermal Comptonization (Ghisellini & Celotti 1999; Giannios 2008); bulk Compton (Lazzati et al. 2000); multicolor blackbody (Peer & Ryde 2010); effects of Compton cooling in the Klein Nishina limit (Daigne et al. 2010)], but there is no prevalent idea yet.

2.5. *Spectral energy correlations*

The time integrated spectrum of the prompt, in νF_ν, has a well defined peak at $E_{\rm peak}$, that correlates with the isotropic energy of the prompt $E_{\rm iso}$: $E_{\rm peak} \propto E_{\rm iso}^{1/2}$ (Amati et al. 2002). When it is possible to measure the jet opening angle of the jet, it is possible to estimate the collimated energy E_γ, that correlates more tightly with $E_{\rm peak}$ ($E_{\rm peak} \propto E_\gamma^b$, with $b = 0.7$ for an homogeneous circumburst density and $b = 1$ for a wind-like profile; Ghirlanda et al. 2004; Nava et al. 2006). This correlation is tight enough to allow to "standardize" GBRs for their use as standard candles to constrain the cosmological parameters. The physical reality of these correlations has been hotly disputed (see Ghirlanda, these proceedings, and reference therein), because selection effects could play

a role. On the other hand, the observations of the same correlations *within single GRBs* (Firmani et al. 2009; Ghirlanda et al. 2010) proves that a physical robust mechanism, still to be understood, is responsible for these spectral–flux (or spectral–energy) correlations.

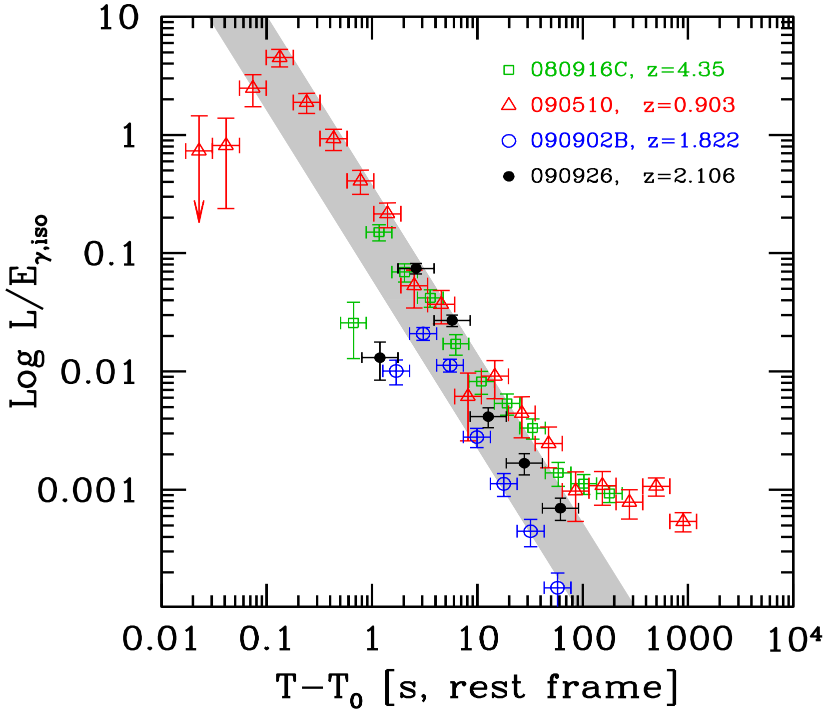

Figure 2. The light curve of the four brightest bursts detected by the *Fermi*/LAT at GeV energies. The luminosity has been divided by the energetics of the emission detected by the *Fermi*/GBM instrument (∼MeV). The time is in the rest frame of the sources. The grey stripe indicates a $t^{-10/7}$ slope. The flattening at long times for GRB 090510 and GRB 080916C indicates the level of the background. Note the similarity of the different light curves.

3. High energy emission

EGRET, in the '90s, detected a handful of GRBs above 100 MeV, and since then we have been left with the question: does this emission belong to the prompt phase or is it afterglow emission produced by the fireball colliding with the circum–burst medium? Or has it still another origin? A puzzling feature of the EGRET high energy emission was that it was long lasting, yet it started during the prompt phase as seen by BATSE. *Fermi*/LAT is $\sim$ 20 times more sensitive, and indeed it detected a dozen GRBs just in its first year of life.

3.1. *Common behaviors*

From the analysis of the first 12 GRBs detected by the LAT we have found these properties (Ghisellini et al. 2010):

Time delay – Usually, the LAT emission lags the emission detected by the GBM (from fractions of seconds, especially for short bursts, to a few seconds).

Long lasting – As already shown by the first EGRET detections, the emission seen by the LAT lasts for a longer time than the emission in the GBM.

No spectral evolution – The average, time integrated LAT photon index is close to 2, with no evidence of strong spectral evolution.

LAT and GBM spectral slopes are often different – The GBM data can be fitted with a Band function, composed of two smoothly joining power laws. All but two bursts (GRB 080916C and GRB 090926) have LAT slopes intermediate between the two slopes of the GBM fit.

LAT fluences are smaller than GBM ones – The majority of bursts have LAT fluences smaller than the GBM ones. The two short bursts GRB 081024B and GRB 090510 and GRB 090902B have comparable LAT and GBM fluences.

Common decay – Fig. 2 shows the light curves of the 4 brightest GRBs with redshift, once the 0.1–100 GeV luminosity is divided by the energetics $E_{\gamma,\rm iso}$ of the flux detected by the GBM. The shaded stripe with slope $t^{-10/7}$ is shown for comparison. These four GRBs are all consistent, within the errors, with the same decay, both in slope and in normalisation. Note that GRB 090510, a short burst, behaves similarly to the other 3 bursts, that belong to the long class, but its light–curve begins much earlier.

3.2. *A radiative fireball?*

The above properties are just what expected by the afterglow emission due to an external shock. The short LAT–GBM delay can be caused by a large Γ (close to 1000), making the fireball to decelerate at early observed times. *The earlier the onset of the afterglow, the brighter the afterglow at early times:* this explains why only 10% of GRBs have been detected by the LAT: they correspond to bursts having the largest Γ–factors.

The relatively steep decay of the LAT light curves is very close to what expected if the fireball is radiative (i.e. most of the dissipated energy is radiated). In this case the bolometric flux in fast cooling decays as $F(t) \propto t^{-10/7} \sim t^{-1.43}$ (Sari et al. 1998; Ghisellini et al. 2010). The slopes of the LAT spectra, being close to unity (in energy), are indeed a good proxy for the bolometric fluxes.

The large peak energy of the GBM flux suggests that electron–positron pairs might play a crucial role for the setting of the radiative regime: a tiny fraction of the prompt photons, scattered (i.e. "decollimated") by the circumburst electrons, are immediately converted into pairs by the high energy photons of the prompt, largely increasing the lepton to proton ratio (Beloborodov 2002). When the shock comes, the dissipated energy can then be given mostly to leptons rather than to protons, and this makes the fireball radiative. Note a key ingredient of this scenario: to produce pairs efficiently, the prompt emission should have a sufficient number of photons above threshold, i.e. above 511 keV.

4. Conclusions

The increase of knowledge can be represented as the volume of an expanding sphere, so it goes like R^3, the cube of the radius. The surface of the sphere is the at the frontier with the unknown, the unexplained, and usually goes like R^2. But for GRBs it seems that that surface is a fractal, whose dimensionality is greater than 2... Is it good or bad? It may be perceived as depressing at first, after all these years of hectic studies, but at a second sight it should be taken as a good opportunity, especially for the younger scientists: there is still something really fundamental to be found out.

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Discussion

Mirabel: What is the fraction of long GRBs with no Supernovae?

Ghisellini: Difficult to say, since there is a clear observational bias (only the nearby ones can be found). I can answer the symmetric question: only $\sim$1% of SN Ibc are associated to a GRB.

Mirabel: What is the range of masses for quark stars?

Ghisellini: One is tempted to associate quark stars to the 2–5 solar mass range, because the observed masses of neutron stars are below 2 solar masses, and the estimates for Galactic black hole masses are larger than 5 solar masses.

de Gouveia: A comment and a question. The comment: you mention the work of Paczynski (2005) proposing a quark star model to explain the engine of GRBs. In 2002 Lugones, Ghezzi, myself and Horvath published an ApJ Letter suggesting the same. I'm glad to see that the GRB community is starting considering this alternative possibility.

The question: you have mentioned also the magnetar model for the engine but we know that there are major theoretical constraints on the production of magnetars. Could you comment on that?

Ghisellini: The Soft Gamma Ray Repeaters are rather convincingly associated to magnetars. These systems can undergo major flares (once per century?) as the one observed on December 27 2004 from SGR 1806–20. If we put SGR 1806–20 at a few tens of Mpc, then we would classify its giant flare as a short GRB. There has been discussion about what fraction of short GRBs are giant flares from magnetars, but both spectral studies (the spectrum should be a blackbody) and correlations with nearby galaxies suggested that this fraction must be small.